

DESCRIPTION

INVERTER APPARATUS

Technical Field

The present invention relates to an inverter apparatus enabled to prevent a simultaneous switching operation of switching elements, which are used and constitute a three-phase inverter incorporated in, for example, a large-capacity UPS, a battery energy storage system, or the like, from occurring during each of the switching elements performs an on/off operation.

Background Art

A three-phase inverter serving as a kind of an electrical power converter incorporated in, for example, a large-capacity UPS, a battery energy storage system, or the like is adapted to perform the conversion of a dc voltage supplied from a dc power supply E, such as a solar battery and a fuel cell, into an ac voltage and to supply electric power to loads UL, VL, and WL, as shown in FIG. 7. The three-phase inverter has a structure in which paired switching elements, which are arranged in an up/down direction, as viewed in this figure, and which correspond to each of a U-phase, a V-phase and a W-phase, for examples, GTO (Gate Turn-Off thyristor) elements UP, UN, VP,

VN, WP, WN are connected in a bridge configuration.

This inverter apparatus is adapted so that the paired GTO elements corresponding to each of the phases are alternately turned on and off, that is, a group of the GTO elements UP, VP, WP, which are shown at upper positions in the figure and correspond to a positive electrode, and a group of the GTO elements UN, VN, WN, which are shown at lower positions in the figure and correspond to a negative electrode, are alternately turned on and off. Consequently, a dc voltage supplied from the dc power supply E is converted into an ac voltage thereby to supply ac power to the loads UL, VL, and WL, as shown in FIG. 7.

A sinusoidal waveform control signal is converted into a pulse gate signal by using a triangular waveform carrier signal. Then, each of the GTO elements UP, UN, VP, VN, WP, and WN is turned on by being applied with a forward bias voltage through the use of the gate driver. Alternatively, each of the GTO elements UP, UN, VP, VN, WP, and WN is turned off by being applied with a reverse bias voltage through the use of the gate signal.

On/off control of these GTO elements UP, UN, VP, VN, WP, and WN is performed so that in a case where the GTO elements UP, VP, WP shown at the upper positions are in an on-state, among the paired GTO elements, and where the GTO elements UN, VN, WN shown at the lower positions are in an off-state, when the GTO elements UN, VN, WN shown at the lower positions are

turned on, the GTO elements UP, VP, WP shown at the upper positions are turned off before the GTO elements UN, VN, WN turn on.

A dead time, in which the GTO elements UP, VP, WP, UN, VN, WN of both of the group shown at the upper positions and that shown at the lower positions are simultaneously brought into a turned-off state, is provided to turn on the GTO elements UN, VN, WN shown at the lower positions after a predetermined interval elapses after the GTO elements UP, VP, WP shown at the upper positions turn off. Consequently, both of the group of the GTO elements UP, VP, WP shown at the upper positions and that of the GTO elements UN, VN, WN shown at the lower positions are prevented from simultaneously being put into a turned-on state. Thus, an occurrence of a dc shortcircuit is prevented (see, for example, Patent Document 1).

Disclosure of Invention

Meanwhile, generally, as shown in FIG. 8, slight stray capacitances C_1 to C_6 are formed between output wires and between the output wire and the earth (or a casing) in the aforementioned inverter apparatus. Therefore, the presence of a dead time, in which the GTO elements of both the group shown at the upper positions and that shown at the lower positions are simultaneously in a turned-off state, as described above, results in discharge of electric charges stored in the stray capacitances to thereby vary the midpoint potential of the GTO

elements corresponding to a phase with respect to that of the GTO elements corresponding to another phase. Incidentally, the apparatus similarly has slight stray capacitances C_7 to C_{10} formed between a gate drive circuit A and each main circuit wire and between the gate drive circuit A and the earth. Thus, the aforementioned variation in the midpoint potential results in variation in the potential of the gate drive circuit. Consequently, a disturbance current is given to a gate current.

Meanwhile, the GTO element has a thyristor structure (pnpn-structure). Thus, the turn-on gain thereof is large, while the turn-off gain thereof is extremely small. Consequently, the turn-on of the GTO element takes several tens of microseconds. Additionally, during that, a large drawing current is necessary for the turn-off. In a case where the gate drawing current in that time becomes unstable due to the disturbance current as described above, the GTO element fails to turn off, and comes to be unable to turn off. In the worst case, there is the possibility of damaging the GTO element.

The aforementioned phenomenon occurs in a case where after the GTO element corresponding to one of the phases and to one of the electrodes turns off, a turn-on command signal for turning on the GTO element corresponding to one of the other phases and to the opposite electrode (in a case where the GTO element corresponding to the one of the phases and to the one of the electrodes is the GTO element UP, the GTO element corresponding

to the one of the other phases and to the opposite electrode is the GTO element VN or WN). Occurrence of the simultaneous switching of this GTO element corresponding to the other phase causes a problem that the gate drawing current becomes unstable.

Accordingly, the invention is proposed in view of the aforementioned problem. An object of the invention is to provide an inverter apparatus enabled to eliminate variation in potential-to-the-ground of the GTO element that corresponds to one of the phases and is performing a turn-off operation, which variation is caused by the switching operation of this GTO element corresponding to the other phase, and also enabled to stabilize the gate drawing current by surely achieving the turn-off of the GTO element.

As technical means for attaining the foregoing object, according to the invention, there is provided an inverter apparatus having a three-phase inverter configured to include paired switching elements connected in a bridge configuration and to convert a power supply voltage, which is supplied from a dc power supply, by the switching elements into an ac voltage. This inverter apparatus features that an inverter control portion has a simultaneous switching prevention function of delaying a turn-on operation of each of the switching elements, which correspond to phases other than a phase corresponding to an optional one of the switching elements and also correspond to an electrode opposite to an electrode corresponding to the

another one of the switching elements, by a predetermined time in a case where a turn-on command signal for turning on each of the switching elements, which correspond to the other phases, is generated within a predetermined time period after the turn-off of the optional one of the switching elements.

Alternatively, the inverter apparatus according to the invention may feature that an inverter control portion has a simultaneous switching prevention function of delaying a turn-off operation of each of the switching elements, which correspond to phases other than a phase corresponding to an optional one of the switching elements and also correspond to an electrode opposite to an electrode corresponding to the optional one of the switching elements, by a predetermined time in a case where a turn-off command signal for turning off each of the switching elements, which correspond to the other phases, is generated within a predetermined time period since turn-on of the optional one of the switching elements.

Alternatively, the inverter apparatus according to the invention may feature that an inverter control portion has a simultaneous switching prevention function of delaying a turn-on operation of each of the switching elements, which correspond to phases other than a phase corresponding to an optional one of the switching elements and also correspond to an electrode opposite to an electrode corresponding to the optional one of the switching elements, by a predetermined time

in a case where a turn-on command signal for turning on each of the switching elements, which correspond to the other phases, is generated within a predetermined time period since turn-off of the optional one of the switching elements, and also delaying a turn-off operation of each of the switching elements, which correspond to phases other than a phase corresponding to an optional one of the switching elements and also correspond to an electrode opposite to an electrode corresponding to the optional one of the switching elements, by a predetermined time in a case where a turn-off command signal for turning off each of the switching elements, which correspond to the other phases, is generated within a predetermined time period since turn-on of the optional one of the switching elements.

According to the invention, the apparatus has the simultaneous switching prevention function. Thus, for example, a turn-on operation of each of the switching elements, which correspond to phases other than a phase corresponding to an optional one of the switching elements and also correspond to an electrode opposite to an electrode corresponding to the optional one of the switching elements, is delayed by a predetermined time in a case where a turn-on command signal for turning on each of the switching elements, which correspond to the other phases, is generated within a predetermined time period since the turn-off of the optional one of the switching elements. Consequently, the simultaneous switching of the

switching elements corresponding to the other phases can be prevented. Thus, the variation in potential-to-the-ground of the GTO element can be prevented from occurring during a turn-off operation thereof. Also, the stabilization of the gate drawing current can be achieved by surely turning off the GTO elements.

Incidentally, according to the invention, not only the Si-GTO element but the SiC-GTO element, which is able to operate at a higher temperature and a higher voltage than the Si-GTO element, can be used as the switching element. Alternatively, a wide-gap semiconductor, such as diamond and GaN, can be used as the switching element.

According to the invention, the apparatus has the simultaneous switching prevention function. Thus, a turn-on or turn-off operation of each of the switching elements, which correspond to phases other than a phase corresponding to an optional one of the switching elements and also correspond to an electrode opposite to an electrode corresponding to the optional one of the switching elements, is delayed by a predetermined time in a case where a turn-on or turn-off command signal for turning off each of the switching elements, which correspond to the other phases, is generated within a predetermined time period since the turn-off or the turn-on of the optional one of the switching elements. Consequently, the simultaneous switching of the switching elements corresponding to the other phases can be prevented. Thus, for

instance, the variation in potential-to-the-ground of the GTO element can be prevented from occurring during a turn-off operation thereof. The stabilization of the gate drawing current can be achieved by surely turning off the GTO elements. A high-quality inverter apparatus can be provided without causing a dc shortcircuit and a damage of the element.

Also, the simultaneous switching prevention function can be realized by either hardware, such as a simultaneous switching prevention circuit including a simultaneous switching prevention logic circuit, a predetermined-post-turning-off-time generating circuit, which is adapted to generate a predetermined post-turning-off time that elapses after turn-off of the optional one of the switching elements, and/or a predetermined-post-turning-on-time generating circuit which is adapted to generate a predetermined post-turning-on time that elapses after turn-on of the optional one of the switching elements, or software installed in the inverter control portion.

Brief Description of Drawings

FIG. 1 is a circuit diagram illustrating an embodiment of the invention, which is an inverter apparatus having a three-phase inverter that includes Si-GTO elements.

FIG. 2(a) is a diagram illustrating a Si-GTO element, and FIG. 2(b) is a diagram illustrating the internal structure of

the Si-GTO element.

FIG. 3 is a circuit diagram illustrating another embodiment of the invention, which is an inverter apparatus having a three-phase inverter that includes SiC-GTO elements.

FIG. 4(a) is a diagram illustrating a SiC-GTO element, and FIG. 4(b) is a diagram illustrating the internal structure of this SiC-GTO element.

FIG. 5 is a waveform chart illustrating an output voltage command signal, a carrier signal, and a gate initial signal.

FIG. 6 is a block diagram illustrating the internal structure of a simultaneous switching prevention circuit shown in FIGS. 1 and 3.

FIG. 7 is a circuit diagram illustrating an example of a three-phase inverter.

FIG. 8 is an explanatory diagram illustrating the generation of stray capacitances in a three-phase inverter.

Incidentally, in the drawings, reference numeral 11 designates an inverter apparatus, reference numeral 12 denotes a switching element (a Si-GTO element), reference numeral 13 designates a dc power supply, reference numeral 14 denotes a three-phase inverter, reference numeral 15 designates an inverter control circuit, reference numeral 16 denotes a PWM pulse generating circuit, reference numeral 17 designates a simultaneous switching prevention circuit, reference numeral 21 denotes a inverter apparatus, reference numeral 22 denotes

a switching element (a SiC-GTO element), and reference numeral 24 designates a three-phase inverter.

Best Mode for Carrying Out the Invention

Hereinafter, an embodiment of an inverter apparatus according to the invention is described in detail. Incidentally, the following description of the embodiment describes a case where Si-GTO elements 12 are used as the switching elements (see FIGS. 1 and 2), and a case where SiC-GTO elements 22, which can operate at a higher temperature and a higher voltage than the Si-GTO elements 12 (see FIGS. 3 and 4).

FIG. 1 exemplifies an inverter apparatus 11 using Si-GTO elements 12 as the embodiment. FIG. 2(a) shows the Si-GTO 12. FIG. 2(b) shows the internal structure of the Si-GTO 12. As shown in FIGS. 2(a) and 2(b), the Si-GTO element 12 has a pnpn structure obtained by bonding p-type semiconductor regions PE and PB and n-type semiconductor regions NB and NE and having junctions J1, J2, and J3, each of which are provided between the associated bonded regions. An anode A is drawn from the p-type semiconductor region PE. A cathode K is drawn from the n-type semiconductor region NE. A gate G is drawn from the p-type semiconductor region PB.

Generally, the Si-GTO element 12 in an on-state can be turned off by letting a gate current flow in a direction opposite to a direction of the current flowing at the turn-on thereof.

That is, when a forward bias voltage is applied between the gate G and the anode A in a state, in which a positive voltage is applied to the anode A and in which a negative voltage is applied to the cathode K and this voltage is blocked by the junction J2, so that the voltage at the gate G is positive with respect to the voltage at the cathode K, holes, the number of which depends upon the magnitude of the gate current, are moved from the gate G to the semiconductor region P_B . Similarly to a state in which a base current is supplied to an NPN transistor portion, electrons, the number of which depends upon the magnitude of each of the gate current and the current amplification factor of the NPN transistor portion, are transported from the semiconductor region N_E to the semiconductor region N_B . The electrons transported to the semiconductor region N_B serve like the base current of a PNP transistor portion. Also, holes, the number of which depends upon the magnitude of each of the number of electrons and the current amplification factor of the PNP transistor portion, are transported from the semiconductor region P_E to the semiconductor region P_B . In this way, what are called carriers, such as holes and electrons, pass through the junction J2 by applying a forward bias voltage between the gate of the NPN transistor portion of the Si-GTO element, which that is in an off-state. Thus, the Si-GTO element cannot maintain the off-state, so that electric current starts flowing, and that

the Si-GTO element turns on.

Meanwhile, the Si-GTO element in an on-state cannot maintain the on-state and is put into an off-state in a case where a part of the holes transported from the semiconductor region P_E to the semiconductor region P_B is drawn from the gate \underline{G} by applying a reverse bias voltage between the gate \underline{G} and the anode \underline{A} so that the voltage at the gate \underline{G} is negative with respect to the voltage at the cathode \underline{K} (the voltage at the cathode \underline{K} is positive with respect to the voltage at the gate \underline{G}), and that electrons, the number of which depends upon the magnitude of the gate current, flow into the cathode \underline{K} from the semiconductor region N_E , and where a total of the current amplification factors of the PNP transistor portion and the NPN transistor portion is equal to or less than 1.

Referring next to FIG. 3, there is exemplified an inverter apparatus 21 employing SiC-GTO elements 22, which can operate at a higher temperature and a higher voltage than the Si-GTO elements 12, as an embodiment. FIG. 4(a) shows the SiC-GTO 22. FIG. 4(b) shows the internal structure of the SiC-GTO 22. As shown in FIGS. 4(a) and 4(b), the SiC-GTO element 22 has a pnpn structure obtained by bonding p-type semiconductor regions P_E and P_B and n-type semiconductor regions N_B and N_E and having junctions J_1 , J_2 , and J_3 , each of which are provided between the associated bonded regions. An anode \underline{A} is drawn from the p-type semiconductor region P_E . A cathode \underline{K} is drawn

from the n-type semiconductor region N_E . A gate \underline{G} is drawn from the n-type semiconductor region N_B .

The SiC-GTO element 22 has a basic structure nearly similar to the aforementioned Si-GTO element 12, and differs from the Si-GTO element 12 in that the base part of the PNP transistor portion of the SiC-GTO element is the gate \underline{G} . Therefore, a turn-on operation and a turn-off operation is performed in the SiC-GTO element 22 by applying a forward bias voltage or a reverse bias voltage between the anode \underline{A} and the gate \underline{G} .

Practically, when a forward bias voltage is applied between the gate \underline{G} and the anode \underline{A} in a state, in which a positive voltage is applied to the anode \underline{A} and in which a negative voltage is applied to the cathode \underline{K} and this voltage is blocked by the junction J2, so that the voltage at the gate \underline{G} is negative with respect to the voltage at the anode \underline{A} (the voltage at the anode \underline{A} is positive with respect to the voltage at the gate \underline{G}), electrons, the number of which depends upon the magnitude of the gate current, flow into the semiconductor region N_B from the gate \underline{G} . Similarly to a state in which a base current is supplied to the PNP transistor portion, holes, the number of which depends upon the magnitude of each of the gate current and the current amplification factor of the PNP transistor portion, are transported from the semiconductor region P_E to the semiconductor region P_B . The holes transported to the semiconductor region P_B serve like the base current of the NPN transistor portion. Also, electrons,

the number of which depends upon the magnitude of each of the number of holes and the current amplification factor of the PNP transistor portion, are transported from the semiconductor region N_E to the semiconductor region N_B . In this manner, what are called carriers, such as holes and electrons, pass through the junction J2 by applying a forward bias voltage between the gate of the NPN transistor portion of the SiC-GTO element 22, which that is in an off-state. Thus, the SiC-GTO element 22 cannot maintain the off-state, so that electric current starts flowing, and that the SiC-GTO element 22 turns on.

Meanwhile, the SiC-GTO element in an on-state cannot maintain the on-state and is put into an off-state in a case where a part of the electrons transported from the semiconductor region N_E to the semiconductor region N_B is drawn from the gate \underline{G} by applying a reverse bias voltage between the gate \underline{G} and the anode \underline{A} so that the voltage at the gate \underline{G} is positive with respect to the voltage at the anode \underline{A} , and where a total of the current amplification factors of the PNP transistor portion and the NPN transistor portion is equal to or less than 1.

Hereinafter, in view of redundant descriptions of the Si-GTO elements 12 and the SiC-GTO elements 22, the Si-GTO element 12 and the SiC-GTO element 22 are designated in common as the GTO elements UP, UN, VP, VN, WP, and WN, as illustrated in FIGS. 1 and 3.

As shown in FIGS. 1 and 3, each of the embodiments, which

are the inverter apparatuses 11 and 21, is configured to include paired GTO elements UP, UN, VP, VN, WP, and WN, which are arranged in an up/down direction, as viewed in these figures, and which correspond to each of a U-phase, a V-phase and a W-phase and are connected in a full bridge configuration, a three-phase inverter 14 or 24 adapted to convert a power supply voltage supplied from the dc power supply 13 into an ac voltage by using the GTO elements UP, UN, VP, VN, WP, and WN, an inverter control circuit 15 adapted to generate and output the output voltage command signals Uref, Vref, and Wref (see FIG. 5) to change the value of an output voltage of the inverter 14 or 24 to a predetermined value, a PWM pulse generating circuit 16 adapted to generate and output drive signals, which cause the GTO elements UP, UN, VP, VN, WP, and WN to perform on/off operations, by performing PWM-modulation on the output voltage command signals Uref, Vref, and Wref, and a simultaneous switching prevention circuit 17 adapted to generate and output a gate signal by delaying the drive signal, which is outputted from the PWM pulse generating circuit 16, by a predetermined time according to conditions that will be described later. Incidentally, an inverter control portion includes the inverter control circuit 15, the PWM pulse generating circuit 16, and the simultaneous switching prevention circuit 17.

Hereinafter, the inverter control circuit 15, the PWM pulse generating circuit 16, and the simultaneous switching

prevention circuit 17, which generate gate signals for the GTO elements UP, UN, VP, VN, WP, and WN to drive the three-phase inverter 11 or 21, are described in detail.

The inverter control circuit 15 is adapted to generate sinusoidal waveform output voltage command signals U_{ref} , V_{ref} , and W_{ref} , which correspond to the phases, respectively, and differ from one another in phase by predetermined amounts, as illustrated in FIG. 5.

The PWM pulse generating circuit 16 is adapted to generate the UP, UN, VP, VN, WP, and WN initial signals (see FIGS. 1 and 3), which are drive signals to cause the GTO elements UP, UN, VP, VN, WP, and WN to perform on/off operations, by performing PWM modulation on the output voltage command signals U_{ref} , V_{ref} , and W_{ref} outputted from the inverter control circuit 15, according to triangular waveform carrier signals K.

As shown in FIG. 6, the simultaneous switching prevention circuit 17 includes post-turning-off Δt_1 generating circuits 18_{UP} , 18_{UN} , 18_{VP} , 18_{VN} , 18_{WP} , and 18_{WN} , post-turning-on Δt_2 generating circuits 19_{UP} , 19_{UN} , 19_{VP} , 19_{VN} , 19_{WP} , and 19_{WN} , simultaneous switching preventing logic circuits 20_{UP} , 20_{UN} , 20_{VP} , 20_{VN} , 20_{WP} , and 20_{WN} , and dead time generating circuits 23_U , 23_V , and 23_W .

The post-turning-off Δt_1 generating circuits 18_{UP} , 18_{UN} , 18_{VP} , 18_{VN} , 18_{WP} , and 18_{WN} are adapted to generate a predetermined time Δt_1 after the turn-off of the GTO elements UP, UN, VP,

VN, WP, and WN. The post-turning-on Δt_2 generating circuits 19_{UP}, 19_{UN}, 19_{VP}, 19_{VN}, 19_{WP}, and 19_{WN} are adapted to generate a predetermined time Δt_2 after the turn-off of the GTO elements UP, UN, VP, VN, WP, and WN.

The simultaneous switching preventing logic circuits 20_{UP}, 20_{UN}, 20_{VP}, 20_{VN}, 20_{WP}, and 20_{WN} are adapted to determine according to each of the UP, UN, VP, VN, WP, and WN initial signals, which are outputted from the PWM pulse generating circuit 16, and the signals outputted from the post-turning-off Δt_1 generating circuits 18_{UP}, 18_{UN}, 18_{VP}, 18_{VN}, 18_{WP}, and 18_{WN} and the post-turning-on Δt_2 generating circuits 19_{UP}, 19_{UN}, 19_{VP}, 19_{VN}, 19_{WP}, and 19_{WN} whether the turn-on operation or the turn-off operation of each of the GTO elements UP, UN, VP, VN, WP, and WN is delayed.

The dead time generating circuits 23_U, 23_V, and 23_W are adapted to generate a dead time according to an output of each of the simultaneous switching preventing logic circuits 20_{UP}, 20_{UN}, 20_{VP}, 20_{VN}, 20_{WP}, and 20_{WN}.

This simultaneous switching prevention circuit 17 is adapted to delay a turn-on operation of each of the GTO elements VN and WN, which correspond to phases other than a phase corresponding to, for example, the GTO element UP and also correspond to an electrode opposite to an electrode corresponding to the GTO element UP, by a predetermined time in a case where a turn-on command signal for turning on each

of the GTO elements VN and WN, which correspond to the other phases, is generated within a predetermined time period Δt_1 since the turn-off of the GTO element UP. Incidentally, the simultaneous switching prevention circuit 17 is adapted to delay a turn-off operation of each of the GTO elements VN and WN, which correspond to phases other than a phase corresponding to an optional one of the GTO elements and also correspond to an electrode opposite to an electrode corresponding to the optional one of the GTO elements, by a predetermined time in a case where a turn-off command signal for turning off each of the GTO elements, which correspond to the other phases, is generated within a predetermined time period Δt_2 since the turn-on of the optional one of the GTO elements.

In this embodiment, which is the inverter apparatus 11 or 21, as illustrated in FIGS. 1 and 3, the inverter control circuit 15 is adapted to generate and output the sinusoidal waveform output voltage command signals U_{ref} , V_{ref} , and W_{ref} , which correspond to the phases, respectively, and differ from one another in phase by predetermined amounts, as illustrated in FIG. 5, to cause the three-phase GTO elements UP, UN, VP, VN, WP, and WN to turn on or off with predetermined timing. The output voltage command signals U_{ref} , V_{ref} , and W_{ref} outputted from this inverter control circuit 15 are PWM-modulated at the PWM pulse generating circuit 16 using the triangular waveform carrier signals K. Thus, the UP, UN, VP, VN, WP, and WN initial

signals, which are used for causing the GTO elements UP, UN, VP, VN, WP, and WN to perform on/off operations, are generated and outputted.

Incidentally, as illustrated in FIG. 5, the simultaneous switching of one of the GTO elements corresponding to one of the phases (for example, the GTO element UP) and the GTO elements (for instance, the GTO elements VN and WN), which correspond to the phases other than the phase corresponding to the one of the phases and to an electrode opposite to an electrode corresponding to the one of the GTO elements, occurs at intersection points P_1, P_2, \dots , at each of which the carrier signal K intersects with two of the three-phase output voltage command signals $U_{ref}, V_{ref},$ and W_{ref} . Thus, variation in potential occurs due to the stray capacitances C_7 to C_{10} (see FIG. 8) in the dead time, in which the GTO elements of both the group shown at the upper positions and that shown at the lower positions are simultaneously in a turned-off state. Consequently, the gate drawing current becomes unstable.

Thus, the simultaneous switching prevention circuit 17 is configured so that the dead time generating circuits $23_u, 23_v,$ and 23_w delay a turn-on operation of each of the GTO elements VN and WN, which correspond to phases other than a phase corresponding to one of the GTO elements and also correspond to an electrode opposite to an electrode corresponding to the one of the GTO elements, by a predetermined time according to

an output of each of the post-turning-off Δt_1 generating circuits 18_{UP}, 18_{UN}, 18_{VP}, 18_{VN}, 18_{WP}, and 18_{WN}, the post-turning-on Δt_2 generating circuits 19_{UP}, 19_{UN}, 19_{VP}, 19_{VN}, 19_{WP}, and 19_{WN}, and the simultaneous switching preventing logic circuits 20_{UP}, 20_{UN}, 20_{VP}, 20_{VN}, 20_{WP}, and 20_{WN} in a case where a turn-on command signal for turning on each of the GTO elements VN and WN, which correspond to the other phases, is generated within a predetermined time period Δt_1 since the turn-off of the one of the GTO elements. Occurrence of the simultaneous switching is prevented by causing the GTO elements to perform on/off operations according to the gate signals outputted from the simultaneous switching prevention circuit 17. Thus, the GTO elements can be caused to perform on/off operations in a condition in which the aforementioned drawbacks due to the stray capacitances C_7 to C_{10} are eliminated.

All of the PWM pulse generating circuit 16 and the simultaneous switching prevention circuit 17 may be implemented by software as a PWM pulse generating circuit with a simultaneous switching prevention function.

Although the specific embodiments of the invention have been described in detail with reference to the accompanying drawings, it is apparent to those skilled in the art that various changes and modifications may be made without departing from the scope and the spirit of the invention.